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Low-Energy Operation of the Lawrence Livermore Electron Beam Ion Traps: Atomic Spectroscopy of Si V, S VII and Ar IX

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Abstract

As part of a project to compile a comprehensive catalog of astrophysically relevent emission lines, we used the low-energy capability of the Lawrence Livermore electron beam ion traps to extend the spectroscopy of neon-like ions and the neighboring charge states to silicon, sulfur, and argon. We present wavelength data of Si V and demonstrate the effect of collisional deexcitation of electric dipole forbidden lines on the 2–3 L-shell spectra of Si V, S VII, and Ar IX.

1. Introduction

Satellite observations in the extreme ultraviolet region provide unique and valuable diagnostic opportunities for astronomers and astrophysicists. The extreme ultraviolet and soft X-ray spectral regions contain a wealth of emission lines that can be used for determining plasma properties and elemental abundances over a wide temperature range. The region between 20 and 140 Å particularly below 80 Å, has received little attention, even in solar measurements. Previous observations by the *Extreme Ultraviolet Explorer* stopped at 70 Å, and crystal spectrometers aboard various solar missions covered the regions below 20 Å. Observations in the soft X-ray region by the *Chandra X-ray Observatory* and *XMM-Newton* are now providing high-resolution measurements, which have far outpaced available atomic databases. There are many more lines in these spectra than can be currently identified, as is graphically illustrated by *Chandra* spectra of Capella [1] and Procyon [2]. Similarly, long-term exposures of HR 1099 have shown a wealth of weak lines that remain largely unidentified as the databases are largely empty. Some of these weak lines raise the “background” level for the brighter, known lines and add uncertainty to their interpretation [3]. Once line assignments are made, these lines will enable determination of elemental abundances from the extreme ultraviolet and soft X-ray data that will complement data obtained in the visible wavelength band.

Contributions to these unidentified lines may come from any astrophysically abundant element, such as magnesium, sulfur, argon, calcium, iron, silicon, and nickel. In many instances, the charge states are fairly low, typically near the closed shell neon-like charge state, e.g. Si V and S VII, or near the closed subshell argon-like charge states, e.g. Fe IX and Ni XI. Calculations are helpful to predict emission from these elements. However, a major problem is that the accuracy of the calculated wavelengths is limited, as the structure of the intermediate ionization stages of all high-Z ions of astrophysical interest are significantly affected by electron-electron interactions, and these ionization stages must be calculated in intermediate coupling. Without experimental guidance such calculations do not provide enough accuracy to identify lines, especially if the density of lines is high.

Electron beam ion traps have been used to measure a wide variety of astrophysically important atomic data [4]. Most measurements have involved highly charged ions, as electron beam ion traps are relatively simple to operate at higher energies, i.e., several keV and above, [5, 6]. Studying low-charge ions is more difficult, as low beam energies, are outside the original design energies of electron beam ion traps. The Berlin EBIT was operated as low as 540 eV to record tungsten data [7], while the NIST EBIT has operated as low as 900 eV to produce Fe XVII [8]. At Livermore, SuperEBIT has been operated as low as 80 eV to investigate various carbon lines in the visible region [9] and EBIT-II as low as 145 eV to produce Fe VII [10]. We used the low-energy capabilities of Livermore’s electron beam ion traps to investigate the low charge states needed to make progress in astrophysical databases. We believe the spectra presented here to be among the lowest energy electron beam ion trap spectra of neon-like ions published to date.

2. Spectroscopic measurements

Spectroscopic measurements were taken on the University of California Lawrence Livermore National Laboaratory electron beam ion trap EBIT-I, which is the original electron beam ion trap. EBIT-I can be operated at the very low voltages (100–200 eV) necessary to produce the charge states we investigated. Different charge states can be produced simply by changing the voltage of the electron beam. As the voltage increases, higher charge states appear when their ionization potentials are exceeded, and lower charge states decline and disappear as they become ionized.

Spectra shown here were taken with either of two grazing-incidence spectrometers combined with a back-illuminated, liquid nitrogen-cooled CCD camera with a one inch square array of $1,024 \times 1,024$ pixels. The first spectrometer [11] employs an average 1,200 line/mm flat-field grating developed by Harada & Kita [12, 13] with a 3° angle of incidence, and has an instrumental resolution of ∼300 (at 100 Å). The second spectrometer [14] employs an average 2,400 line/mm flat-field grating developed by Harada & Kita [12, 13] with a 1.3° angle of incidence, and has an instrumental resolution of ∼300 (at 25 Å) to ∼500 (at 50 Å).

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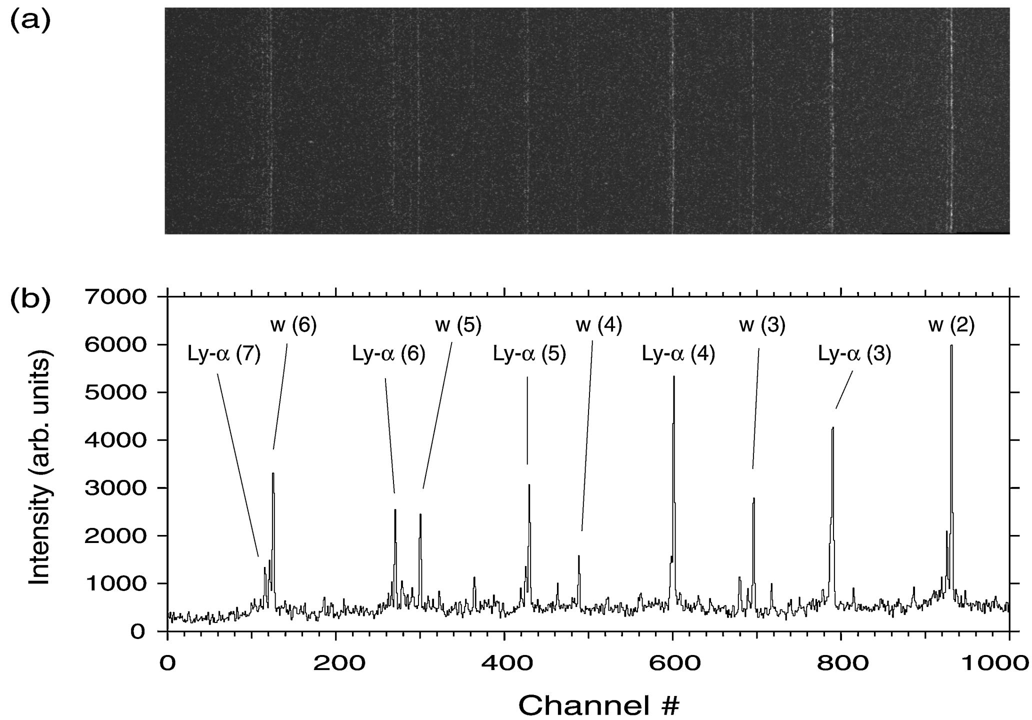

Fig. 1. Calibration spectrum of nitrogen, showing prominent N VII Lyman-α lines and the N VI w resonance lines. Range covers approximately 55–185 Å. (a) Image from CCD camera. (b) Spectrum obtained from (a) after filtering out cosmic rays and subtracting background.

The spectra were calibrated using the well-known K-shell emission lines of nitrogen, carbon, and oxygen, in particular the C VI, N VII, & O VIII Lyman-α lines, and the C V, N VI, & O VII resonance lines commonly referred to as w, as described by Beiersdorfer *et al.* [11]. These lines were observed in the third through seventh orders (57–173 Å) with the 1,200 line spectrometer and in first order (19–40 Å) with the 2,400 line spectrometer. A typical set of calibration lines is seen in Fig. 1.

Spectra were also taken without an active trap, dubbed the inverted-trap mode [15], i.e., without a potential applied to the trap electrodes. These spectra enabled us to determine the level of background emission (including visible light from the electron-gun filament, to which the CCD camera is sensitive), which was then subtracted from the raw data to yield background-corrected spectra. We also filtered out stray cosmic rays, which are ubiquitous in any instrument sensitive to X-ray wavelengths. The relative sizes of the emission lines for each charge state can be determined after correction for differing sensitivity of the detector at different wavelengths [10, 16].

Figure 2 shows a spectrum of sulfur taken at 300 eV. The dominant lines in the spectrum are from neon-like S VII. At this energy, some S VIII, with an ionization potential of 328 eV, is also produced, as seen in the figure. This is not surprising as there is a spread in beam energy of about 30 eV.

Figure 3 shows a spectrum of silicon taken at 175 eV. At this energy, only neon-like Si V is produced. No higher charge states are yet excited, as the ionization potential for Si VI is 205 eV. Some of the lines in the 2p-nd Rydberg series are also apparent in this spectrum. To the best of our knowledge, Si V is the lowest charge neon-like spectrum recorded to date on an electron beam ion trap. S VII is the second lowest. Before these measurements, Ar IX, recorded at 400 eV, was the lowest Z neon-like spectrum measured. That spectrum was also measured on EBIT-I [17].

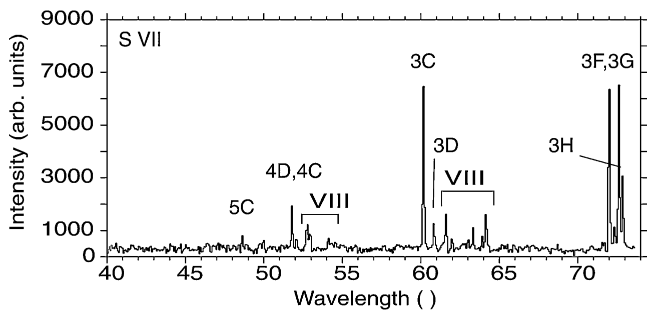

Fig. 2. Spectrum of neon-like S VII taken at a beam energy of 300 eV.

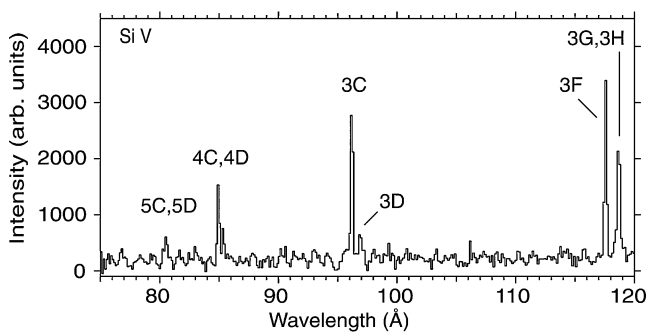

Fig. 3. Spectrum of neon-like Si V taken at a beam energy of 175 eV.

3. Results and discussion

In Table I, we present line identifications and wavelengths of the neon-like Si V. We compare our measured data with wavelengths given in the most commonly used astrophysical databases, MEKAL [18, 19] and CHIANTI [20, 21]. Agreement is generally within 10 mÅ. The exception is the 3F line, which

Table I. *Summary of Si V emission data.*

Label	Transition	Measured λ (Å)	St. Error	MEKAL λ (Å)[a]	$\Delta\lambda^{b}$	CHIANTI λ (Å)[c]	$\Delta\lambda^{d}$	GRASP λ (Å)[e]	$\Delta\lambda^{f}$
...	...	...	...	80.000	...	...	...	...	...
5C	5d → 2p	80.544	0.019	...	...	...	...	82.3	1.756
5D	5d → 2p	80.780	0.013	...	...	...	...	82.6	1.820
...	...	81.119	0.016	...	...	...	...	...	...
4C	4d → 2p	85.177	0.008	85.175	−0.002	...	...	86.7	1.523
4D	4d → 2p	85.578	0.011	85.579	0.001	...	...	87.2	1.622
...	...	...	...	90.500	...	...	...	...	...
3C	3d → 2p	96.438	0.007	96.437	−0.001	...	...	98.2	1.762
3D	3d → 2p	97.159	0.018	97.143	−0.016	...	...	100.3	3.141
...	...	...	...	98.210	...	...	...	...	...
3F	3s → 2p	117.846	0.006	117.820	−0.026	117.820	−0.026	120.6	2.754
3G	3s → 2p	118.950	0.007	118.960	0.010	...	...	121.8	2.850
3H	3s → 2p	119.871	0.089	...	...	...	...	122.2	2.329

[a] [18, 19].
[b] $\lambda_{MEKAL} - \lambda_{EBIT}$.
[c] [20, 21].
[d] $\lambda_{CHIANTI} - \lambda_{EBIT}$.
[e] [22].
[f] $\lambda_{GRASP} - \lambda_{EBIT}$.

differs by 26 mÅ. The wavelengths in MEKAL and CHIANTI are from (the same) solar measurements.

We also list in Table I the results of calculations performed with the general relativistic atomic structure program GRASP [22]. The calculations were performed using the average level (AL) mode and including levels of the type $1s^2 2\ell^7 n\ell'$ with $n \leq 5$. The differences between theory and measurement are several Ångström.

Although the density in EBIT-I was estimated to be only about 10^{10}–10^{11} cm^{-3}, this density is sufficiently high to dramatically diminish the intensity of the $(2p^5_{3/2}3s_{1/2})_{J=2} \rightarrow (2p^6 3s^2)_{J=0}$ transition labelled 3H. In Si V, the line is close to vanishing. The ratio of the intensity of this line to that of the $(2p^5_{1/2}3s_{1/2})_{J=1} \rightarrow (2p^6 3s^2)_{J=0}$ transition, labelled 3F, is a mere 0.08. In S VII, the 3H line is somewhat larger and clearly discernable (cf. Fig. 2). Here we find a ratio of 0.29. For comparison, the ratio in Ar IX, which is much less affected by density effects because of its higher nuclear charge, is 0.87. In Table II we list various ratios including $2p - 3s$ transitions in Si V, S VII, and Ar IX.

We note that the 3H line is not the only line that is affected by density effects. Collisional deexcitation also diminishes the $(2p^5_{1/2}s_{1/2})_{J=0} \rightarrow (2p^6 3s^2)_{J=0}$ transition, labelled $\mathcal{B}$. This transition was discovered and described by Beiersdorfer, Scofield, & Osterheld [23]. It only exists because of the relatively high magnetic field in the ion trap. The line can be easily discerned in the S VII spectrum shown in Fig. 2. But it is not seen in the Si V spectrum shown in Fig. 3.

Table II. *Ratios of neon-like emission lines.*

Ratio	Si V	S VII	Ar IX
3H/3F	0.08	0.29	0.87
3H/3G	0.09	0.32	0.89
$\mathcal{B}$/3F	<0.05	0.17	0.22
($\mathcal{B}$ + 3H + 3G)/3F	0.96	1.35	2.07

4. Conclusions

Extension of the spectroscopy of neon-like ions and the neighboring charge states to silicon, sulfur, and argon using an electron bean ion trap requires low-energy operation. As we show, such low-energy operation is routinely possible at Lawrence Livermore National Laboratory. We have used this capability to record the lowest-Z spectrum of a neon-like ion to date obtained from an electron beam ion trap. The measurements allowed us to present new wavelength data and to demonstrate the effect of collisional deexcitation of electric dipole forbidden lines. Identification and wavelength tables of the L-shell transitions in neighboring charge states needed to fill the close-to-empty astrophysical databases for sulfur and silicon will be presented in the near future.

Acknowledgments

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